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J. W. Meyer

Program Description – Radar Observations of the Planets

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

PROGRAM DESCRIPTION – RADAR OBSERVATIONS OF THE PLANETS

J. W. MEYER

Division 3

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LEXINGTON MASSACHUSETTS

ABSTRACT

An approach to the construction of a radar employing the 120-foot Haystack antenna at a wavelength of approximately 4 cm., a transmitter capable of producing 500 Kw of average power, and a maser preamplifier for the receiver is described. The system is expected to have a threshold (signal-to-noise in a 1-cps filter) of 355 decibels. Extended integration can increase this factor by about 10 decibels. This radar performance will permit measurements on the inner planets of the solar system throughout their orbital period. Measurements on Jupiter can also be attempted, and a possible detection of Saturn is implied. Experiments exploiting this performance are described, including the conduct of a 4th test of general relativity, the precision determination of the orbits of the inner planets, a measurement of the astronomical unit with increased accuracy, better determination of planetary masses and radii, and measurements on planetary surfaces. These measurements are not only of interest to astronomers and cosmologists but also of critical importance to the accurate guidance and navigation of vehicles in space. The roles played by the (L-band) Millstone radar tracker, and the (UHF) ionospheric radar in current space research are also briefly discussed.

J. W. Meyer

Accepted for the Air Force
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PROGRAM DESCRIPTION – RADAR OBSERVATIONS OF THE PLANETS

Introduction

The recent addition of the Haystack Research Facility to Lincoln Laboratory's Millstone Hill Field Station complement of large and powerful radars has given a new and complementary dimension to the Station's capability of making deep space measurements. The fullest utilization of the implied performance of its 120-foot diameter precision parabola requires a 10 db improvement in radar sensitivity. A transmitter producing from one-half to one megawatt of average power at 4 cm wavelength would provide the bulk of this improvement. This report describes important space experiments that become possible with a radar designed around the large antenna and the powerful transmitter.

The advantages of time of flight and doppler measurements that radar can provide over conventional astronomical techniques for orbital studies are well known. The capability of measuring scattered power, time and doppler dispersion in the radar echo, polarization rotation and depolarization effects, and the correlation of these observations allow not only accurate measurement of planetary orbits, but also the deduction of characteristics of the planets themselves from orbital measurements and radar echo analysis, e.g., planetary masses, radii, and certain surface features. The radar described here, for example, will permit measurements on Mercury all the way around its orbit. With this capability the 4th Test of General Relativity suggested by Shapiro*, can be carried out. We will be able to determine the astronomical unit in terms of light seconds to an accuracy of 1 part in 10^8 with a year's data. The relativistic advance in Mercury's perihelion could be determined to within 0.2%, and a number of other important planetary and satellite investigations could be carried out.

* Shapiro, I. I., Phys. Rev. Ltrs., 13, No. 26, pp. 789-791 (December 28, 1964)

Since 1959, about 80 tracking operations have been conducted with the Millstone L-band tracker in support of NASA programs. Among these operations were tests with Echo I and II, and the tracking of IMP-1 during a recent several-month period when it was not transmitting. Millstone has skin-tracked Cosmos 41 to 10,000 miles. With sophisticated data processing techniques we have been able to see Syncom II at about 23,000 miles. This performance is achieved by a radar capable of tracking a one-square meter target at 5000 nautical miles. In equivalent terms, i.e., single pulse detection, the performance of the high power Haystack radar would permit extending skin tracking range on a one-square meter target to 10,000 nautical miles; performance which would assist in large measure the keeping track of silent high altitude satellites. The deduction of the mass of an artificial satellite from accurate orbital determinations and radar cross section measurements would also be possible.

The remaining major facility at the Millstone Hill Field Station, the 220-foot Zenith antenna and UHF (440 mcps) radar has been used for the systematic study of the upper ionosphere by means of incoherent scattering techniques. These measurements have been correlated with those made from the topside sounder in Alouette, and with electron temperature measurements made by Explorer XVII.

All the facilities at the Millstone Hill Field Station are integrated for mutual support operation and their flexibility permits operations over a wide frequency region. Therefore, in addition to the important scientific work that can be accomplished, significant support of the nation's space program could also be forthcoming.

I. The Radar Equation

In its simplest form, the radar equation is deduced as follows: the power density (watts m^{-2}) produced by a transmitter power P_o (watts) feeding an antenna with gain G is

$$S = \frac{P_o G}{4\pi R^2} \text{ watts } m^{-2}. \tag{1}$$

If the cross section for isotropic scattering σ , (m^2) intercepts this flux, the power density (watts m^{-2}) at the receiving aperture will be

$$Sr = \frac{S\sigma}{4\pi R^2}, \text{ watts } m^{-2}, \tag{2}$$

hence the received power P_r for an effective receiving aperture $A_{eff}(m^2)$

$$P_r = \left(\frac{P_o G}{4\pi R^2}\right)\left(\frac{\sigma}{4\pi R^2}\right) A_{eff} \cdot \text{ watts} \tag{3}$$

Since the gain of an antenna is related to its effective area, viz:

$$G = \frac{4\pi A_{eff}}{\lambda^2}, \tag{4}$$

one sees that for parabolas of given diameter the gain increases inversely as the wavelength squared. This is true until an exponential term depending on the surface tolerance achieved in manufacture and operation begin to dominate, viz:

$$G = \frac{4\pi A_{eff}}{\lambda^2} \exp - \left(\frac{4\pi\varepsilon}{\lambda}\right)^2 \tag{5}$$

where ε is the rms surface tolerance deviation from a best fit paraboloid*. This clearly shows the importance of precision to increasing the received signal by going to shorter wavelengths. The gain is maximum when $\lambda = 4\pi\varepsilon$, at which point the value of the gain is:

$$G_{max} \approx \frac{A_{eff}}{10\pi}\left(\frac{1}{\varepsilon}\right)^2. \tag{6}$$

Since the effectiv e area is proportional to the diameter of the parabola squared (D^2), the maximum gain of an antenna

$$G_{max} \propto \left(\frac{D}{\varepsilon}\right)^2. \tag{7}$$

The impact of these considerations on the magnitude of P_r (Eq. (3)) clearly shows the importance of large, precision parabolas to deep space radar.

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*Ruze, J., NEREM Record, p. 166 (1964)

In planetary radar astronomy, it is convenient to express the isotropic scattering cross section, σ , as a fraction of the project area of the planet under study (π a^2), where a is the radius of the planet:

$$\sigma = \kappa (\pi a^2)$$

where $0.01 \leq \kappa \leq 0.15$ for the several planets over a wide range of frequency. The isotropic scattering cross section is a function of wavelength, the scale of the roughness, and the reflectivity of the surface material.

The demonstration of radar detectability is often done in terms of a power "budget" in decibels. In the power budget, a term called the path loss (the ratio, in db, of the power fed into the terminals of a unity-gain transmitting antenna to the echo power received by an antenna of unit (1 m^2) aperture) along with the required signal-to-noise ratio are in the debit column while the radar characteristics which overcome this path loss are in the credit column.

The path losses for the three nearer planets are listed in Table I. The kappa factors used in these tabulations are those estimated for X-band wavelengths. If one assumes the same kappa factor for all planets, and computes the detectability based on relative distance and projected area alone, the detectability of the solar system planets relative to Venus are given in Fig. 1. The variations in path loss for 1955 and 1956 for Mercury are shown in Fig. 2.

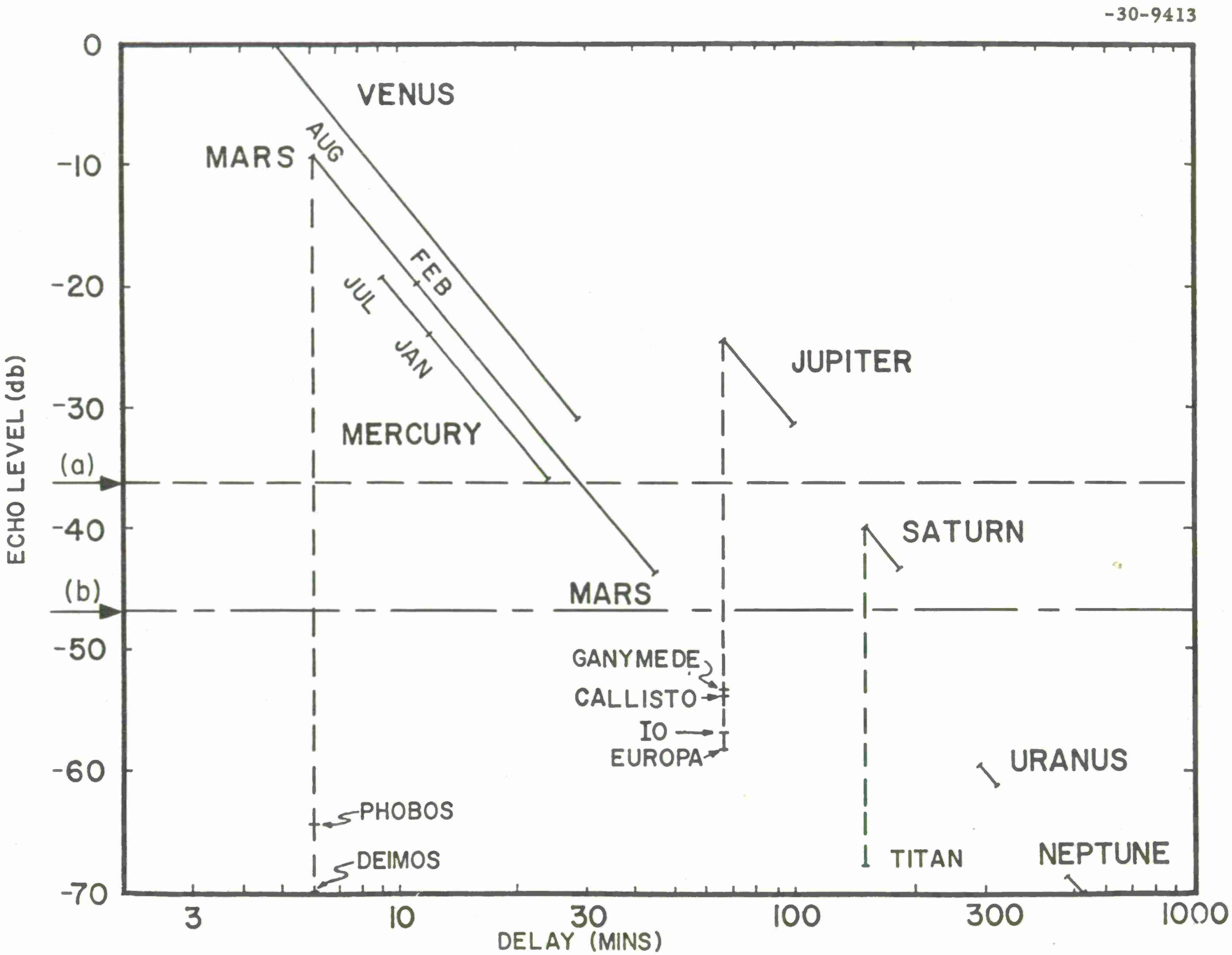
The radar transmitted signal design is done within the limitations set by the peak and average power capabilities of the transmitter, the kind of resolution in time and frequency desired, and the possibilities of coherent or incoherent integration in either real or non-real time. Since the received function is, in general, the convolution of the transmitted waveform function and the scattering function, the appropriate receiver design is a matched filter for greatest sensitivity. Planetary or satellite roughness and rotation rates limit the degree to which the receiver bandwidth can be narrowed to improve its sensitivity. These bandwidths have been estimated or measured and are also shown in Table I.

TABLE I

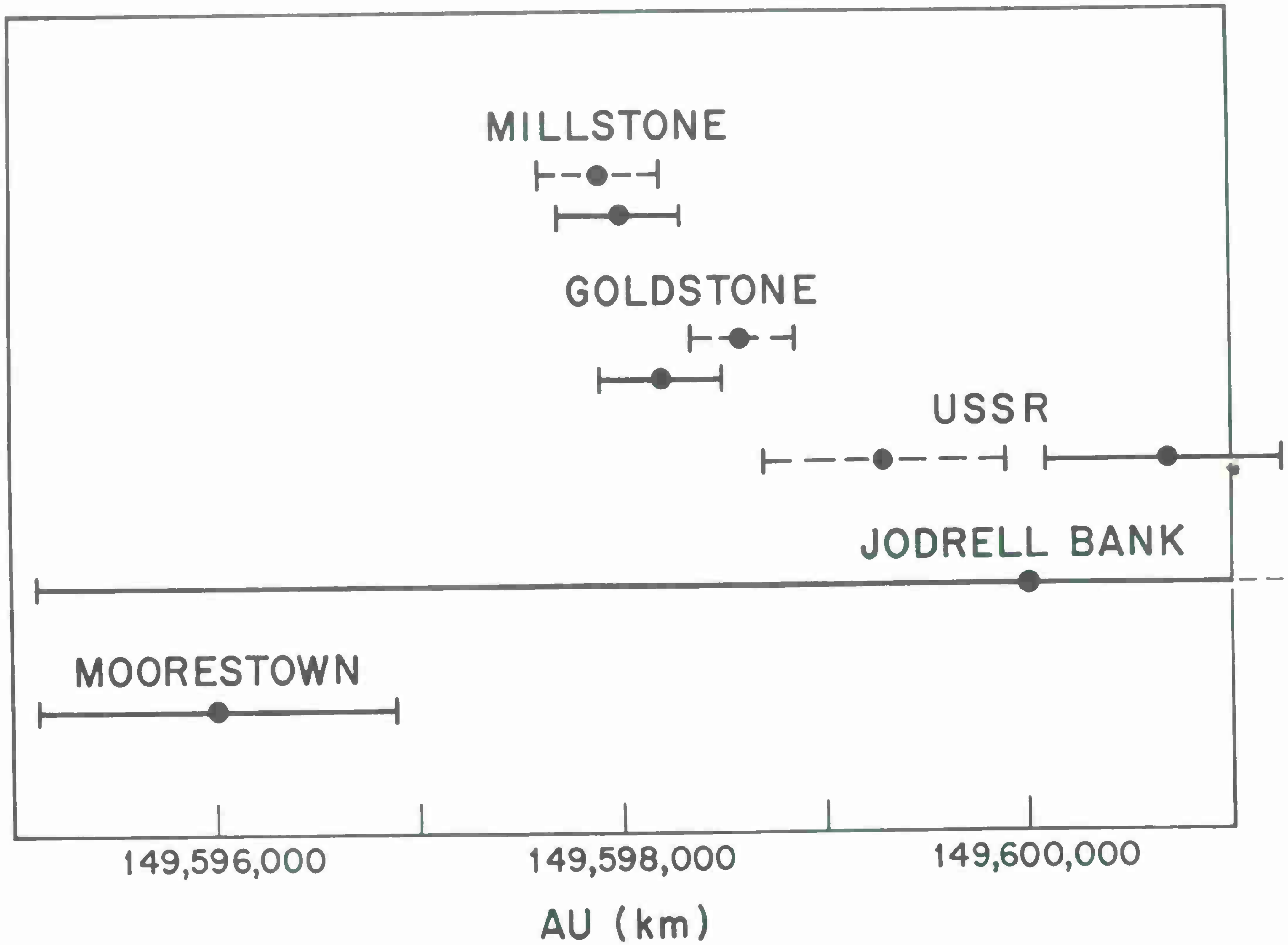
FACTORS INFLUENCING THE CW RADAR DETECTION OF PLANETS

	Mercury	Venus	Mars
Assumed isotropic scattering cross section ($\sigma = K\pi a^2$)	$0.05\ \pi\ a^2$	$0.01\ \pi\ a^2$	$0.03\ \pi\ a^2$
Mean Diameter ($D = 2a$)	4842 Km	12, 300 Km	6, 665 Km
Projected Area ($A = \pi\ a^2$)	$1.84 \times 10^7 Km^2$	$1.19 \times 10^8 Km^2$	$3.49 \times 10^7 Km^2$
Depth in Radar Time ($T = \frac{2a}{c}$)	16 msec	41 msec	22 msec
Echo half-power bandwidth	20 cps	100 cps	200 cps*
Path loss $\left(L = 10 \log \frac{\sigma}{(4\pi)^2 R^4} \right)$			
minimum range	339 db	326 db	341 db
maximum range	355 db	357 db	363 db

*The high rotation rate of Mars would yield about 2000-cps bandwidth from limb-to-limb scattering. Since most of the power is returned from a restricted frontal area on the planet, the choice of the narrower 200-cps filter gives greater overall sensitivity.



1. The detectabilities of the planets relative to that of Venus expressed in decibels. CW threshold (S/N = 0 db) after 10,000 seconds integration; present (a), upgraded (b).



2. The value for the astronomical unit derived from the several radar observations on Venus in 1961 is indicated with the probable error involved. The error in the AU deduced from astronomical measurements exceeds the size of this chart by about an order of magnitude.

The presently planned and the upgraded Haystack radar parameters listed in Table II indicate that radar measurements could be made on the three closer planets all the way round their orbits, albeit with varying quality due to limited signal-to-noise ratio* at extended ranges. From these estimates, one might expect Jupiter to be within range of the system during closest approach and with the possibility that Saturn would be visible to the upgraded system at nearest approach.

The present radar cannot reliably observe any of the listed planets (Table I) round its orbit even for CW detection in which no range resolution is attempted.

Where We Stand

One of the most significant contributions of radar measurements on Venus, the first planet to be observed, was the refinement by several orders of magnitude of the determination of the astronomical unit. Recently, in fact, a working group of the International Astronomical Union, consisting of five astronomers, from Germany, England, France, the Soviet Union, and the United States*, was assigned the task of compiling a revised set of astronomical constants taking the latest data of all kinds into account, the first revision since 1896. One of the most important problems facing this group was the establishment of the solar parallox - the angle that the earth's equatorial radius subtends at a distance of one astronomical unit. The 1896 value assigned was 8.80 seconds of arc. In 1950, E. Rabe studied the motion of the asteroid Eros and deduced a value of $8''.7984 \pm 0''.0004$, which was in disagreement with the results of worldwide triangulation measurements on Eros conducted in 1930-31 which gave the value $8''.790 \pm 0''.001$.

*Experience has shown that at least a 6 db signal-to-noise ratio is required for reliable measurements.

**Germany, W. Fricke (Chairman)
England, G. A. Wilkins
France, J. Kovalevsky
Soviet Union, A. A. Mikhailov
United States, D. Brouwer

TABLE II

HAYSTACK CW RADAR PARAMETERS

FREQUENCY (MCPS) 7750

	Present	Upgraded
Antenna Gain (db) (65.4 db - 1.2 db Dome Loss	64.2	
Antenna Aperture (db over 1 m^2	25.0	
Transmitter Average Power (dbw)	50.0	57
System Temperature, T (^{o}K)	145	75
kT (dbw)	-207.0	-210
Waveguide and Other Losses (db)	1.2	1.2
System Threshold (Signal=Noise in a 1-cps) Filter	345	355
System Threshold against ☿ in 20 cps Filter after 10^4 Seconds Integration	355	365

The Figure of 145^{o}K is obtained as follows

	Present	Upgraded
Receiving Line Loss (≈ 0.2 db)	20^{o}K	10^{o}K
Receiver Temperature (estimated)	75^{o}K	15^{o}K
Contribution from Radome (estimated)	15^{o}K	
Background Noise Temperature including Component from the Sun	35^{o}K	
Total	145^{o}K	75^{o}K

Careful analysis of radar results* has yielded a value of the AU of about 499.005 light sec. (the time required for light to travel a distance of 1 AU) which, when using a value of 299,792.5 km/sec for the speed of light gives about 149,598,000 km as a measure of the AU. The accuracy of some of the measurements analyzed is about 3 parts in 10^8 (see Fig. 3).

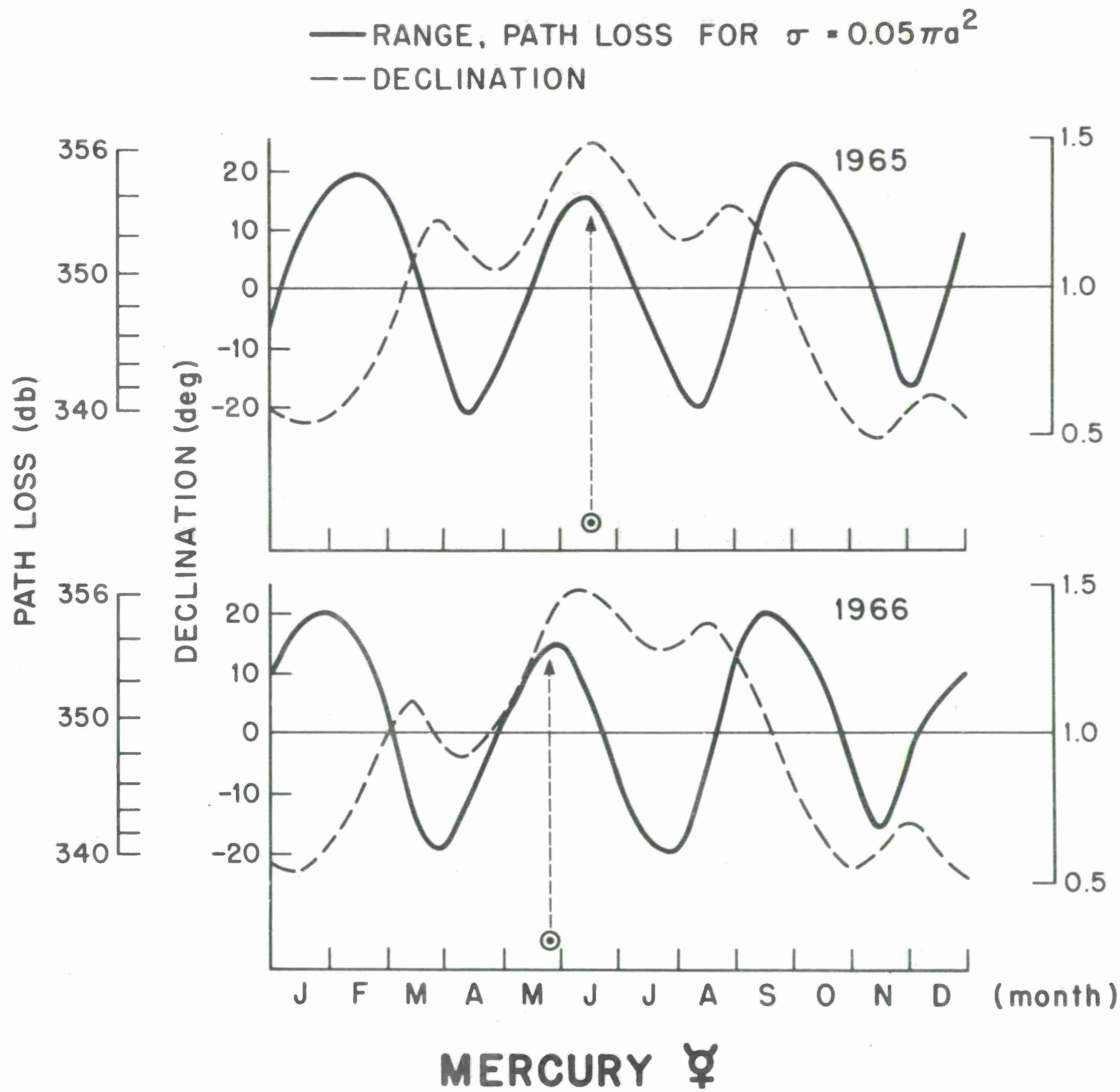
The IAU working group decided not to choose any one numerical result and recommended** that astronomers adopt a round number 149,600,000 km as the equivalent of one AU, 299,792.5 kilometers per sec as the speed of light, 6,378.160 kilometers as the equatorial radius of the earth (giving 8.79 seconds of arc as the solar parallax) and 1/81.30 as the ratio moon mass to earth mass pending the results of further radar measurements. The working group decided not to recommend any changes in the adopted values for the masses of the principal planets.

A comparison as shown in Fig. 4 of the computed Venus ephemeris with that measured by radar has revealed residuals far in excess of the errors of measurement. The harmonicity appearing on this "S" curve, has been shown to be a result of truncating too soon the series representing the ephemeris. When additional terms are included, the smooth curve of Fig. 5 results. Studies of the doppler spectrum of Venus reflections, such as those shown in Fig. 6, lead to the establishment of the retrograde rotation of the planet with a period of 247 $\pm$ 5 days, see Fig. 7. The results have been precise enough to allow the experimental verification of the second order correction to the longitudinal doppler shift, Fig. 8.

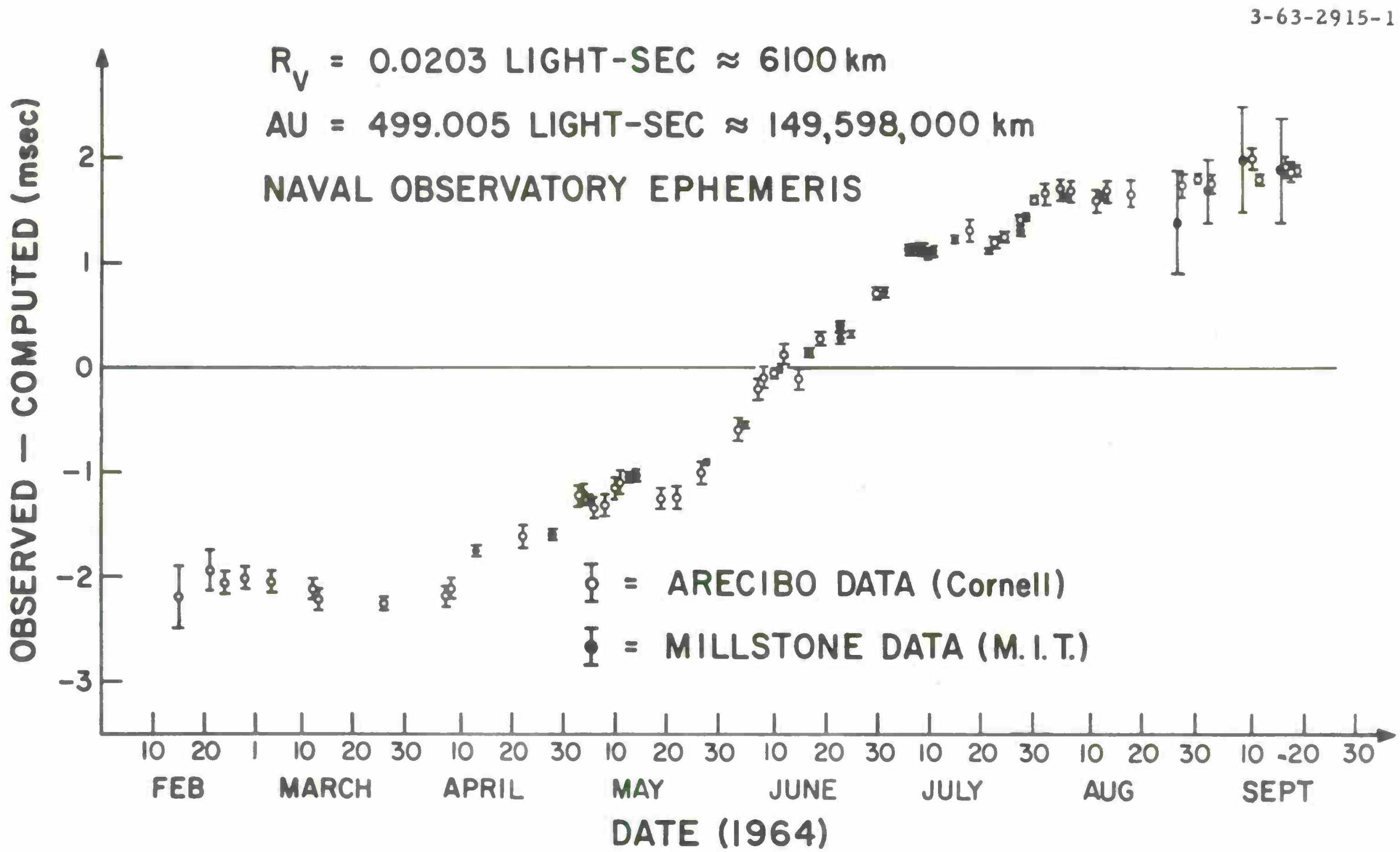
Investigations of Mercury and Mars, while in a much more preliminary stage, have yielded an AU determination compatible with the above. Indications

*Shapiro, I. I., Hamburg Meeting IAU, 27 Aug. 1964

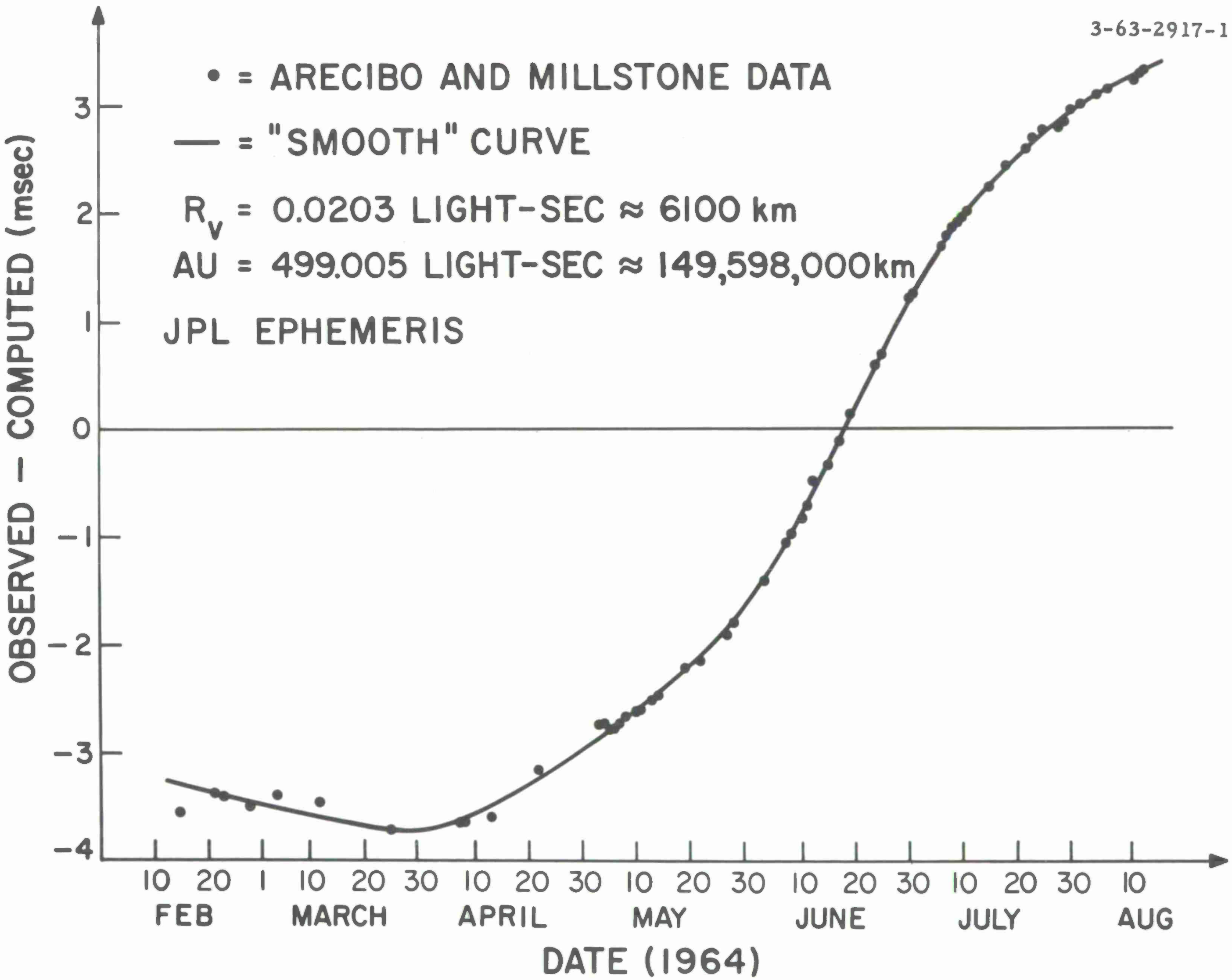
**Trans. IAU of 12th Gen. Assembly, pp. XLIX-LIV



3. Range, path loss and declination expected for Mercury for the years 1965 and 1966 as a function of the calendar year.

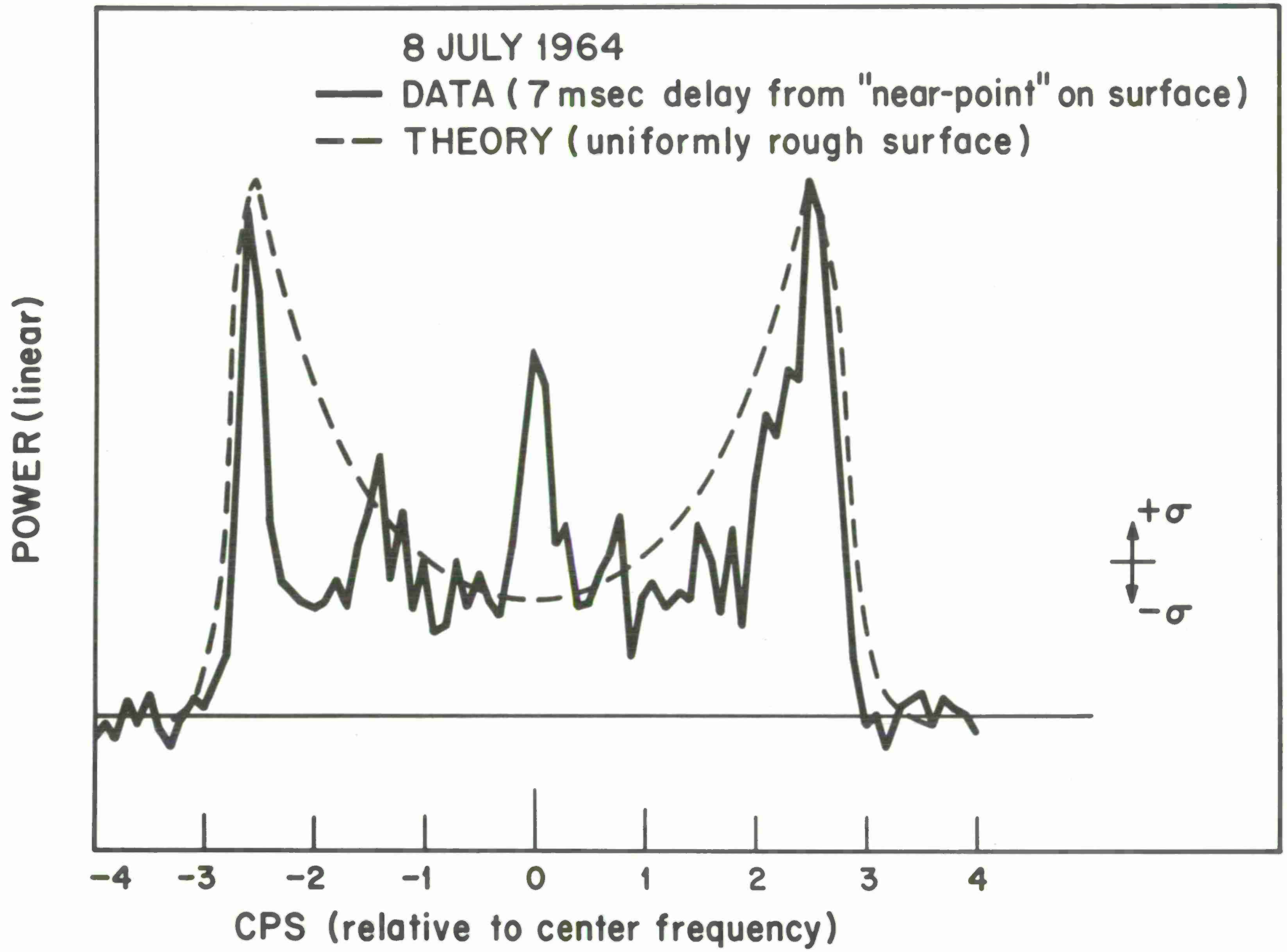


4. Earth-Venus time delay residuals resulting from the comparison of the computed Naval Observatory ephemeris and the radar measurements. The residuals are seen to be well in excess of the errors in measurement.



5. The inclusion of more terms of the series in computation cause the quasi-monthly periodicity in the residuals to disappear.

3-DO-2227



6. Doppler spectrum of echo energy reflected from an annulus on the surface of Venus located 1051 Km (7 msec) from the near point of Venus.

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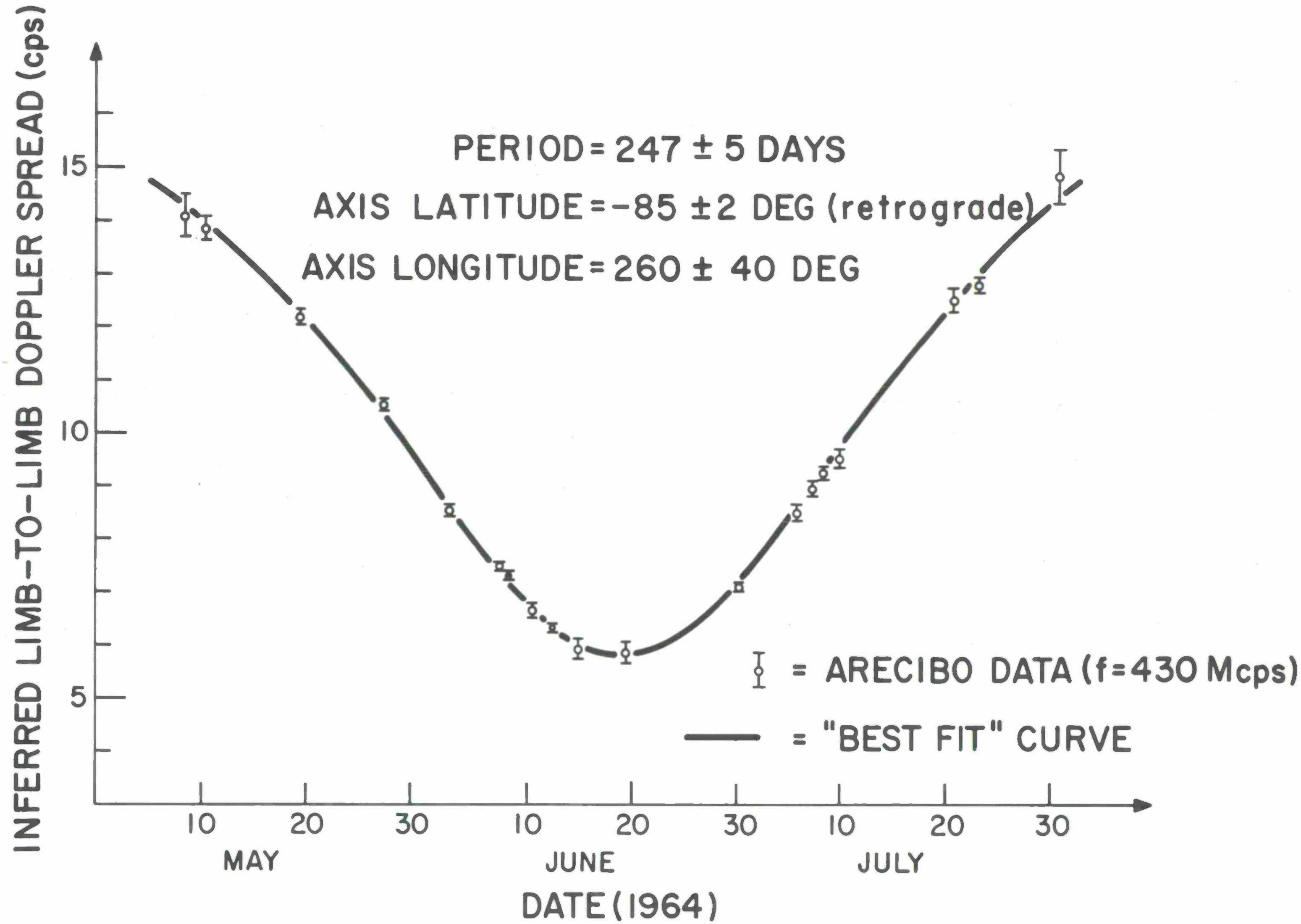
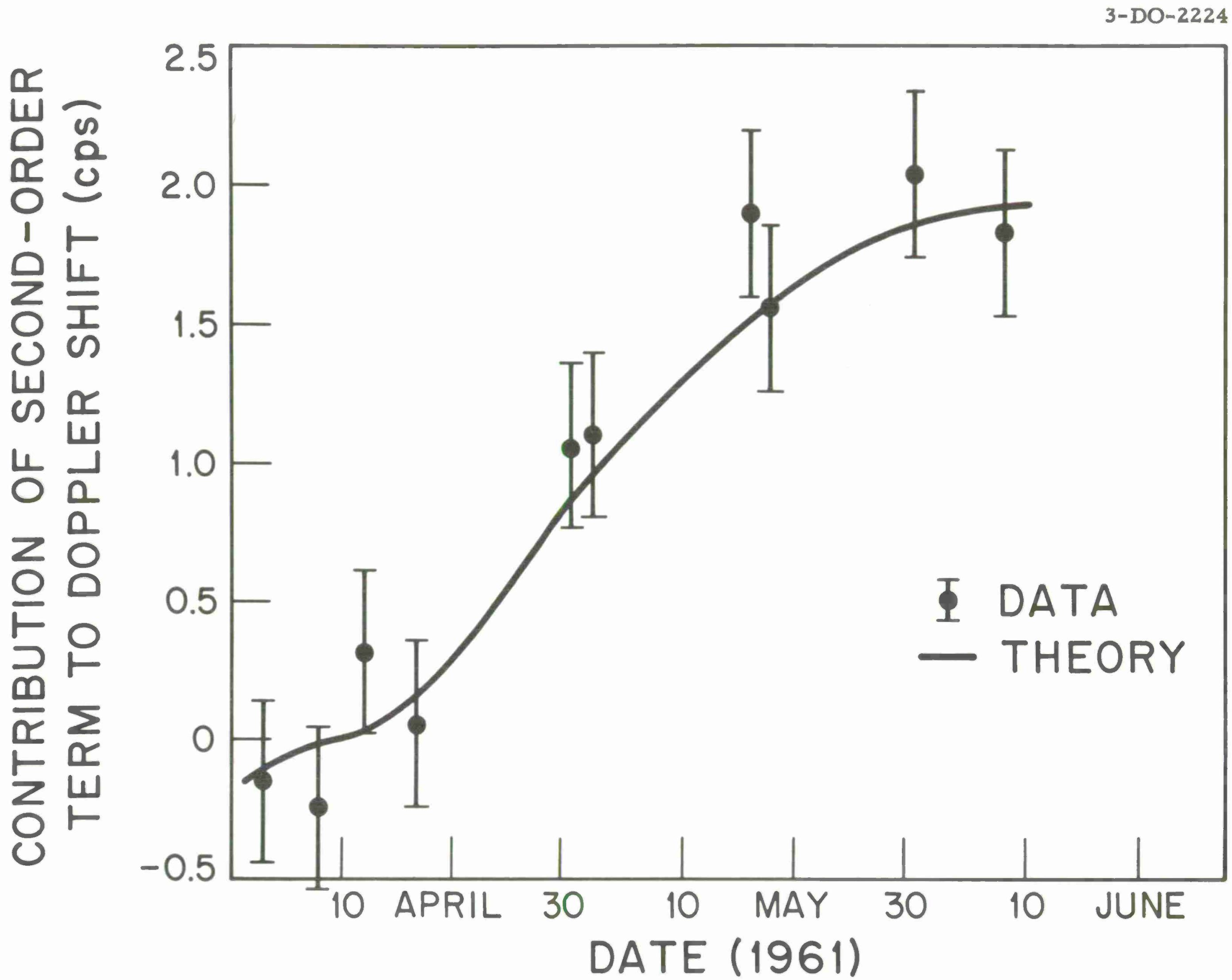


7. The variation in inferred limb-to-limb doppler spread as a function of time permitting the deduction of the rotation period of Venus.



8. A comparison of the second order doppler shift as computed from theory with that measured by radar which constitutes an experimental verification of the second order doppler shift.

are that Mercury is much rougher than the moon while Mars appears smoother. Mercury appears to be ahead in its orbit by one second of heliocentric arc. A plot of the Earth-Mercury time delay residuals is shown in Fig. 9.

The mean distance, earth center to moon center has been measured to within plus or minus a kilometer.

Radar detection of Jupiter has been reported but with such poor signal-to-noise ratio that the experiment needs repeating with improved radar characteristics.

Our satellite observation capability with the Millstone Radar is illustrated in the elevation, azimuth, range, and doppler plots on Cosmos 41 shown in Figs. 10 and 11, and the echo returned from Syncom II shown in Fig. 12 at a range of about 36,000 km. Results from coherent integration on this target indicate a frequency stability of the order of 0.01 cps in 1.295×10^9 cps or about one part in 10^{11}. This kind of stability is very important to doppler measurements and the use of coherent integration techniques, both in astronomy and in satellite work.

The random errors in the Millstone radar performance are presently estimated at

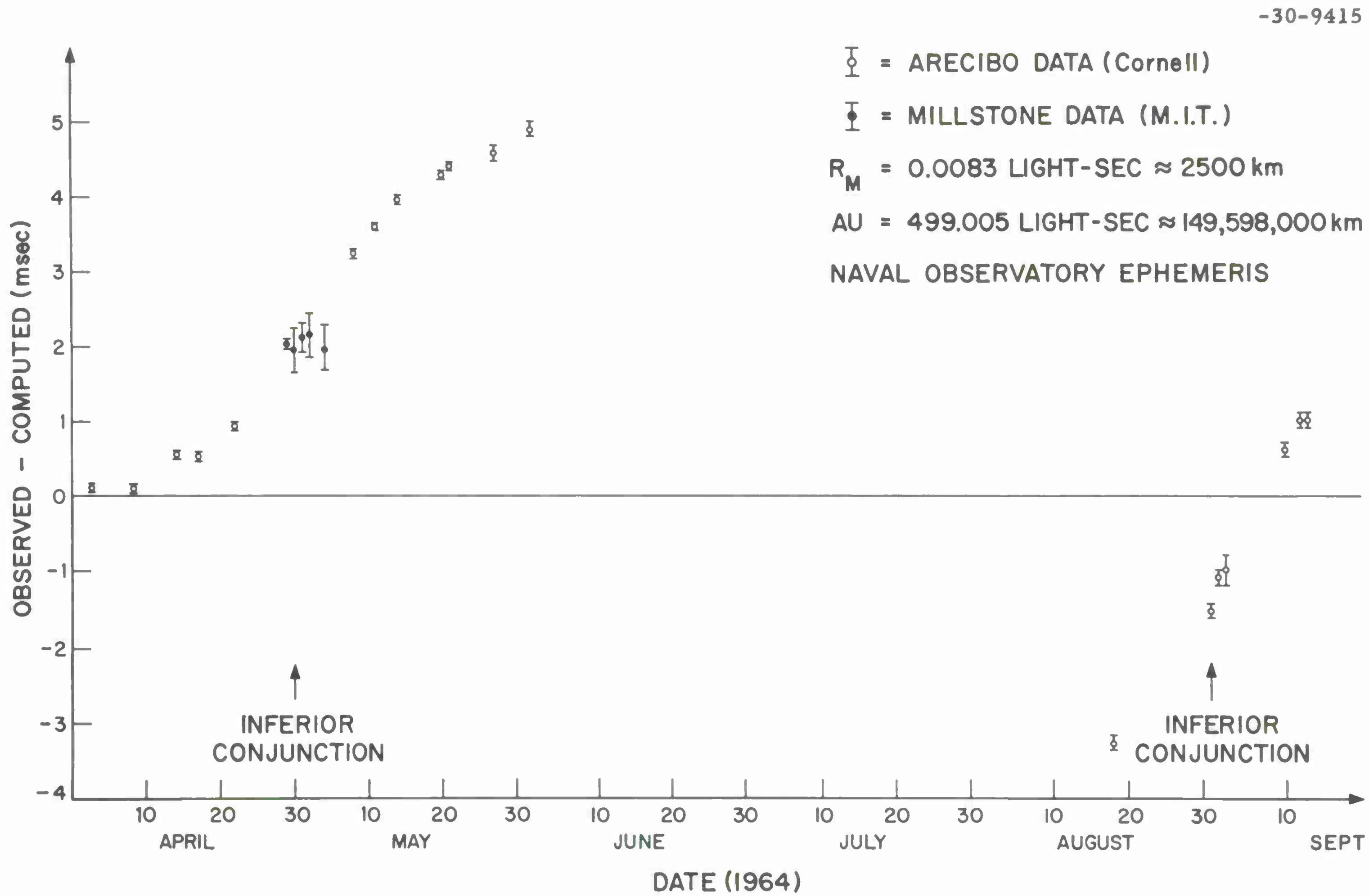
σ az = σ eℓ = 1 min. arc

σ range = 1 naut. mi. (6080 ft.)

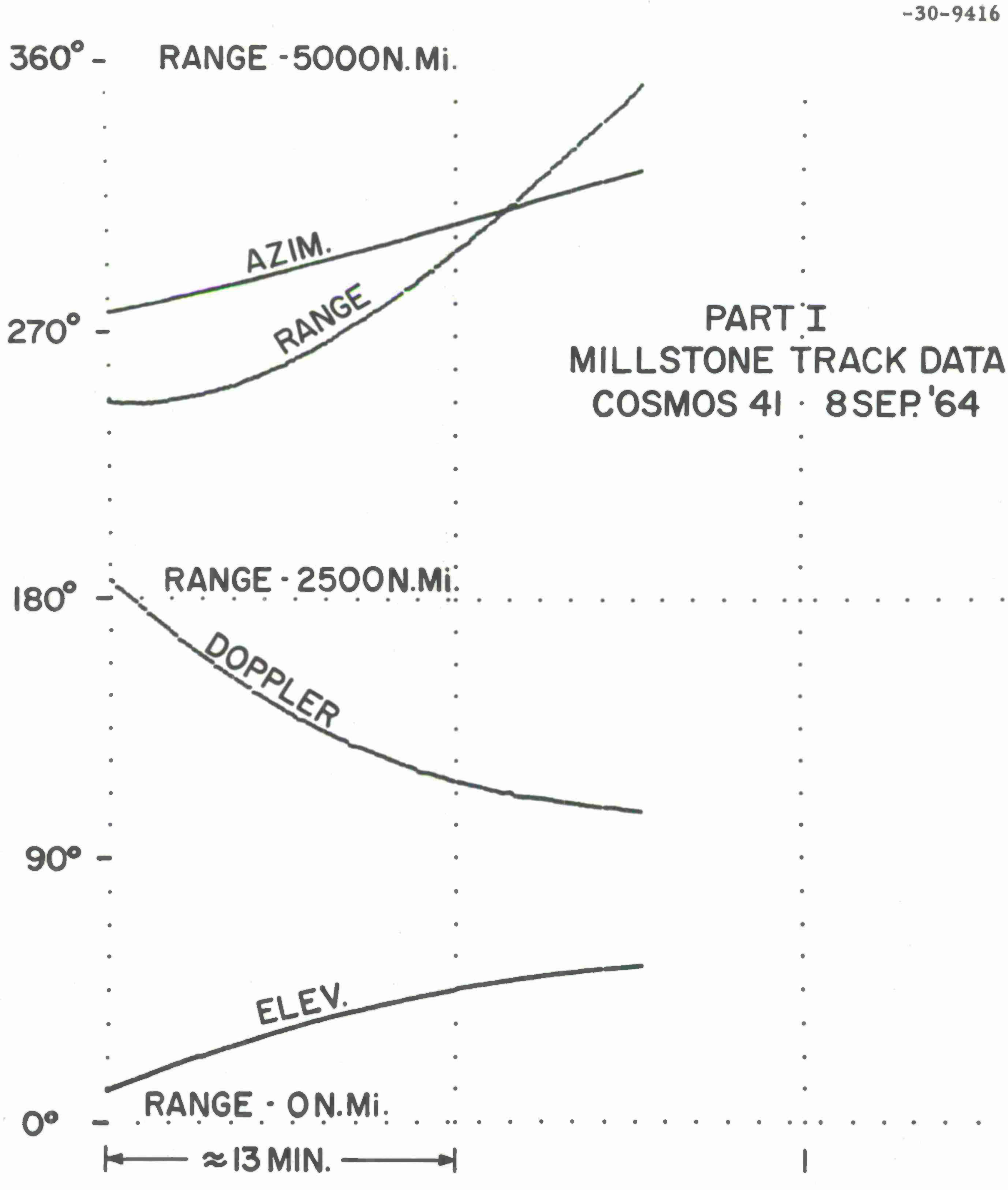
σ doppler = 3 ft. per sec.

Based upon two long tracks of a polar-orbit satellite in a 2000 mile high-circular orbit, Millstone data will permit prediction of the location and velocity of the target nearly two days after the start of the first track with errors as follows:

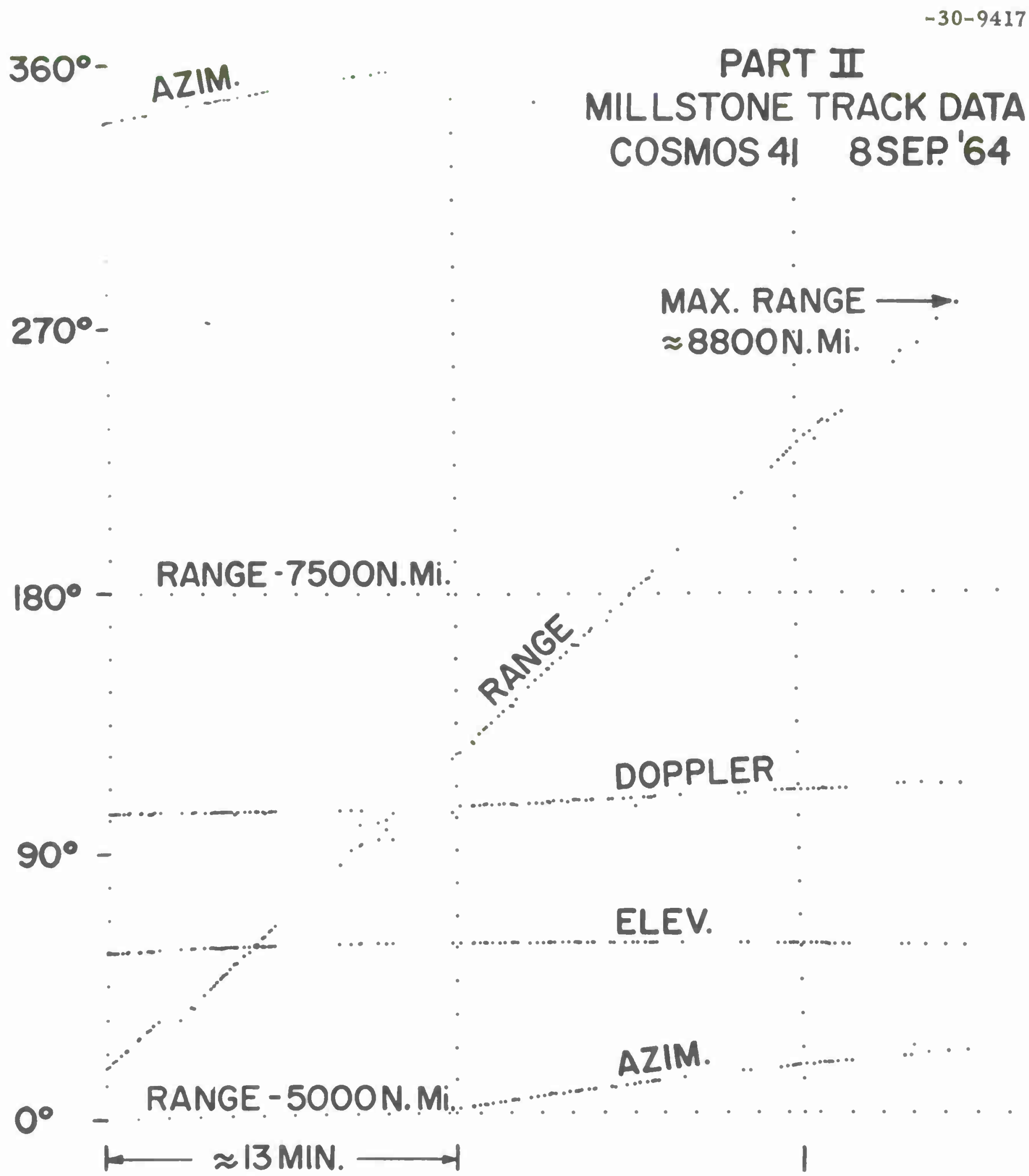
σ_x(ft.) = 675	σ_x(ft/sec) = 1.02
σ_y(ft.) = 1342	σ_y(ft/sec) = 1.71
σ_z(ft.) = 3156	σ_z(ft/sec) = 0.9



9. Earth-Mercury time-delay residuals based on the difference between the times computed using the Naval Observatory ephemeris and those measured by radar. The residuals are seen to be far in excess of the indicated errors of measurement.



10. The calligraph plot of the tracking of Cosmos 41 out to 5000 nautical miles on 8 September 1964.



11. A second calligraph plot, with 5000-10,000 nautical miles range scale, of the tracking of Cosmos 41 out to about 8800 nautical miles on 8 September 1964.

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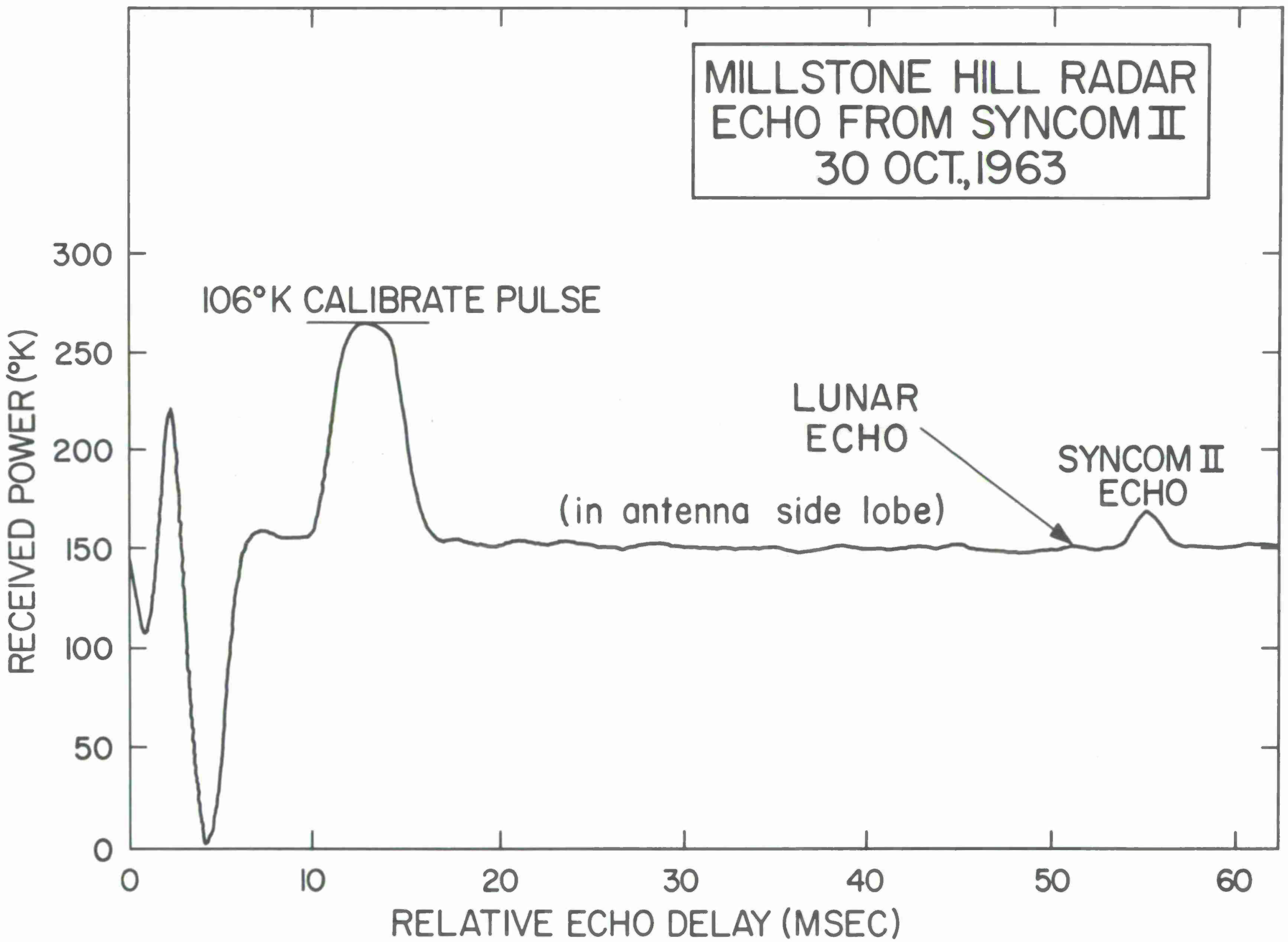


12. The Syncom II echo with the Millstone radar employing long term integration. An indication of the sensitivity of the method is given by the detection of a lunar echo in an antenna side lobe.

given a redundant data precision orbit determination program* for the SDS-9300 computer.

New Program Horizons

An improved site capability, consisting of a more sensitive Haystack Radar, plus precision determination programs for Millstone Radar would permit the following kinds of experiments.

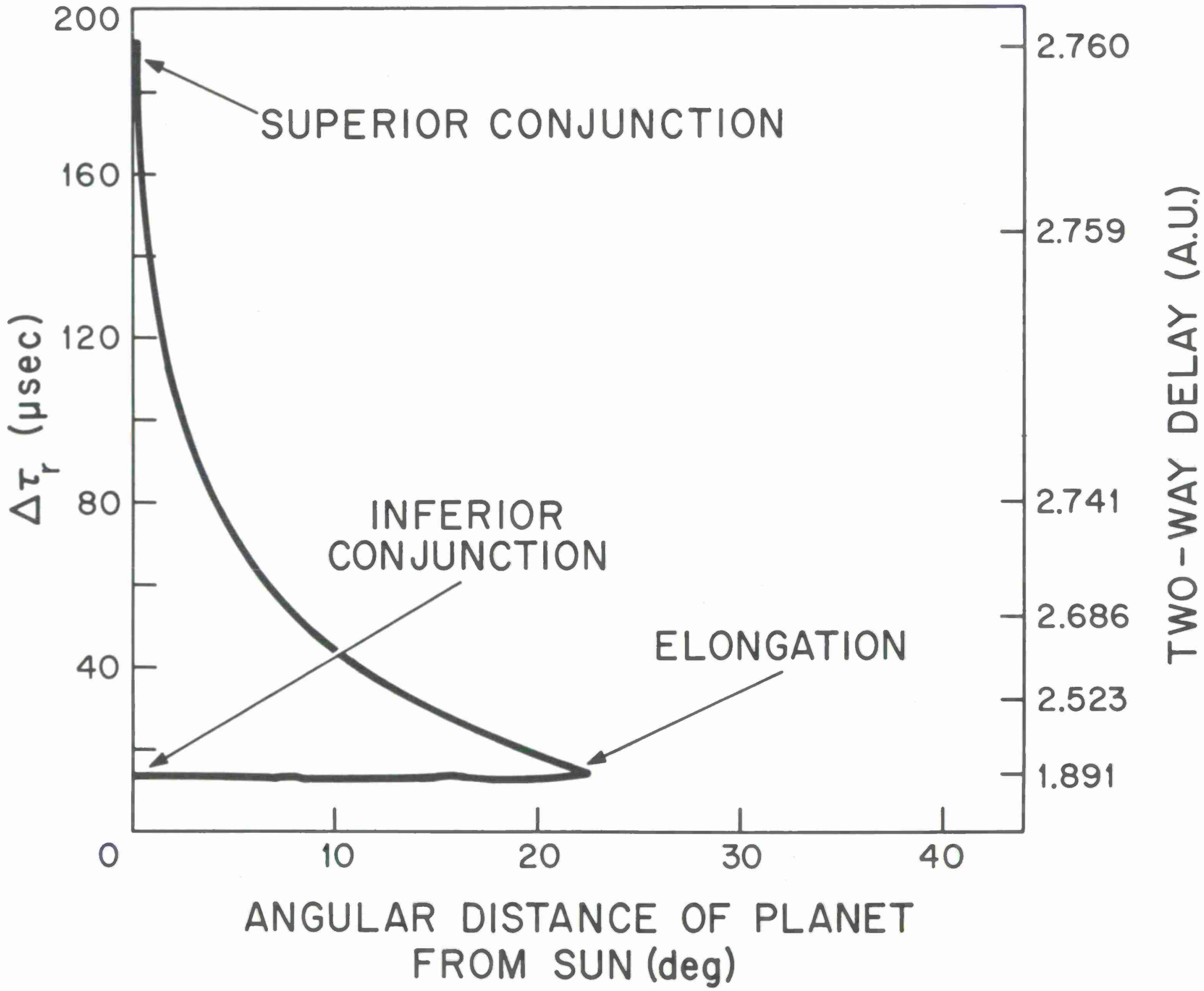
I. The systematic tracking of the near planets of the solar system would allow experiments in the following areas:

A. General Relativity. The test of Einstein's prediction that the speed of light decreases with increasing gravitational potential could be carried out with an error of only 5 to 10% on a single measurement basis; repeated measurements through successive superior conjunctions would probably enable the rms error to be reduced to the 1% level. This experiment would be performed by measuring the interplanetary time delay as a function of earth-sun-planet configuration; in this way, the entire functional dependence of the Einstein prediction can be tested, albeit with decreasing accuracy as the earth-sun-planet orientation changes from superior conjunction to elongation**. See Figs. 13 and 14.

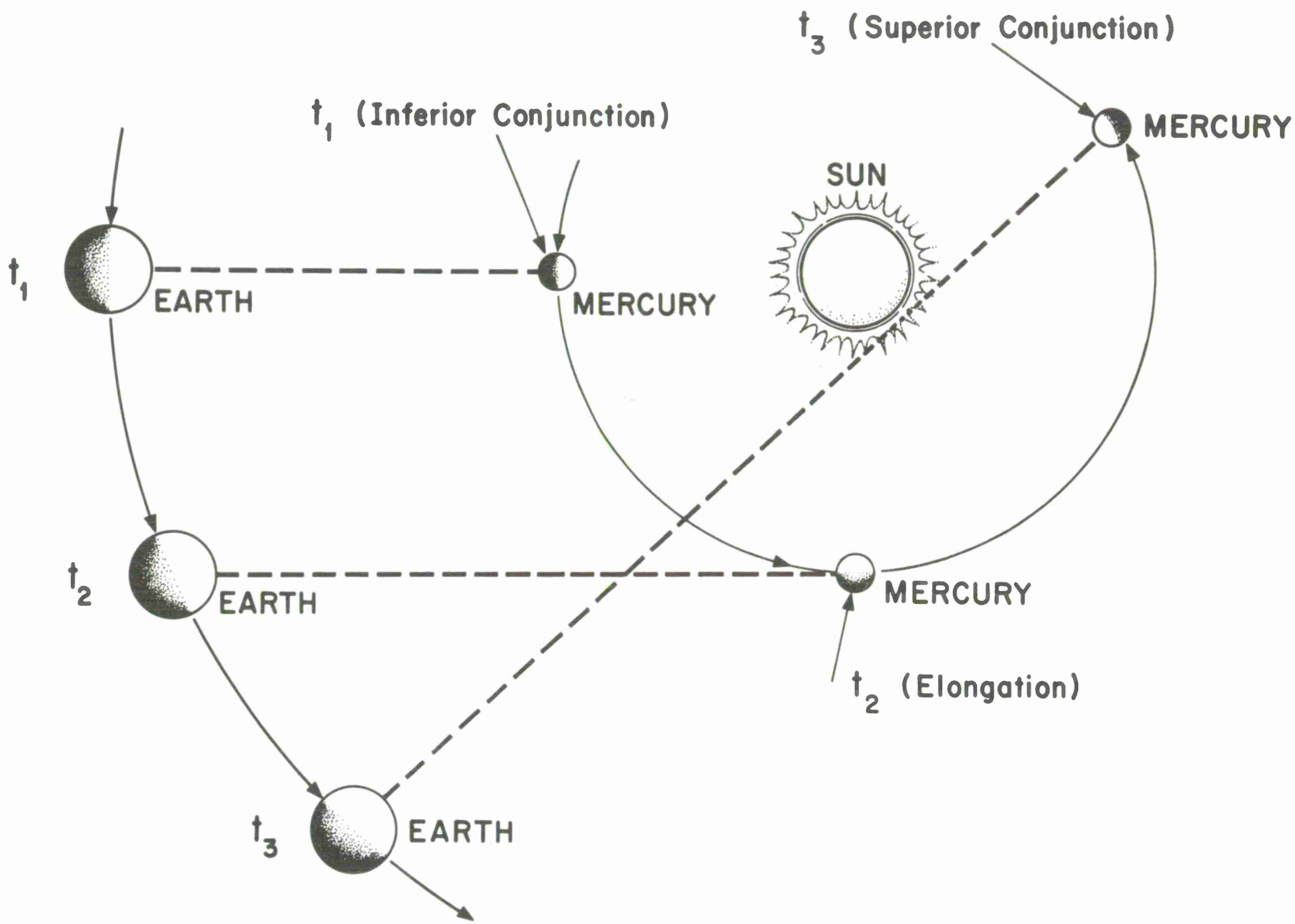
*Error analysis carried out with ESPOD (Electronic Systems (Division USAF) Precision Orbit Determination) program on Lincoln Laboratory's IBM 7094 computer.

**This prediction of general relativity can also be tested through Doppler-shift measurements: Since the relativistic effect on time delay is itself a function of time, a corresponding Doppler-shift is thereby introduced. This shift is a positive (or negative) maximum when the distance from the sun to the light path decreases (or increases) most rapidly. At X-band the maximum magnitude is about 4 cps. Because of the noncoplanarity of the planetary orbits and the "blinding effect" of the sun on the radar, the maximum "practical" shift will be no more than 1 cps. Although the necessary frequency stability (better than 1 part in 10^{10}) is presently achievable, the ability to locate the center frequency from the Doppler broadened return from a rotating planet to the required accuracy may not be so readily obtained.

-30-9419



13. The variation of the realtivistic effect on the radar time delays is plotted for the period between the inferior and the superior conjunction of Mercury.



14. The geometry of the relativity experiment is illustrated here. The minimum effect of the solar mass on the radar propagation time occurs at t_1, inferior conjunction, and the maximum effect at t_3, superior conjunction.

B. Time Dependence of G. Any change in the gravitational constant G that exceeds about 3 parts in 10^9 per year should be detectable from a few years of time-delay observations of the inner planets.

C. Astronomical Unit. Of course, accomplishing (B) implies the ability to determine the astronomical unit in terms of light-seconds to 1 part in 10^8 with about one year's data. This accuracy could be achieved.

D. Planetary Orbits. Time-delay and Doppler shift observations of the inner planets, continued over several years, should enable two orders of magnitude improvement in knowledge of some of the orbital elements of each. In particular, the rate of advance of Mercury's perihelion should be determinable to about a tenth of a second of arc per century.

E. Planetary Masses. From the perturbations of Mercury on the orbits of Venus and earth and from the perturbations of Venus on the orbits of Mercury and earth, the masses of both Mercury and Venus can be obtained. Although the accuracy of the determination of Venus' mass will not approach the accuracy claimed on the basis of the Mariner II flight, the determination of Mercury's mass may be an order of magnitude or so better than has heretofore been possible.

F. Planetary Radii. Earth-Venus and Earth-Mercury time-delay measurements should lead to determinations of target planet radii with errors of the order of 1-10 km. If the X-band reflections from Venus are from the clouds instead of from the surface, comparison with other (lower frequency) radar data will yield the height of the reflecting layer above the surface.

G. Artificial Satellites. The mass of a high-altitude earth satellite could be estimated from accurate orbital determinations and radar cross-section measurements. The accuracy of the mass determination will depend critically on the assumed relation between the optical and the radar cross section of the satellite. (The optical cross section is involved since the effect of sunlight pressure on the orbit must be used to estimate the satellite area-to-mass ratio.)

H. Interplanetary Plasmas, Solar Corona, and Planetary Ionospheres. Because of the plasma effect, time-delay measurements with errors in the several μ sec range, cannot yield comparably accurate "vacuum distance" determinations at radar frequencies as low as Arecibo's. On the other hand, from near-simultaneous, equivalently accurate, observations made at Haystack and Arecibo, the plasma effect can be deduced. By this technique the ionospheres of the inner planets* can perhaps be studied and certainly the corona of the sun and the interplanetary plasma (for example, by making observations of Mercury from elongation to superior conjunction). Mainly integrated electron densities would be determined, although some information on magnetic fields might be obtained from Faraday rotation effects. From sets of integrated electron densities, the average radial distribution of electrons around the sun could be determined.

II. With detailed investigations of the moon and near planets the following could be done:

A. Moon.

1. Detailed mapping of small regions to determine relative roughness (Arecibo and Haystack).

2. Combined polarization and mapping studies to determine depth of penetration of the waves (Brewster's angle) and dielectric constant (Millstone and Haystack). Note: These and other experiments are described in Group Report 1964-65, "Draft Program Description for Radar and Radiometric Lunar Surface Studies," dated 20 November 1964.

*If X-band reflections from Venus are not from the surface, this discussion is inapplicable. But important information about the clouds of Venus could undoubtedly be obtained were, e.g., ice crystals therein to reflect significant microwave power.

3. An interesting measure of the scattering characteristics of the moon would be obtained from a bistatic experiment in which a lunar orbiting satellite would relay back the energy scattered from Haystack illumination of the moon. Lincoln Laboratory might wish to build a payload which would permit this kind of measurement.

B. Venus.

1. Least mean squares reduction of all radar distance measurements to yield improved orbital elements and a still better value for the AU. This should also determine the radius to $\pm$ 10 km.

2. More detailed (and higher power) studies at 3.6 cm are required to check previous Lincoln work (Haystack required). If effects of Venus' atmosphere are responsible for the apparent 1% cross section, careful X-band observations should reduce the number of atmospheric models possible that will fit all the observations.

3. Improved mapping (upgraded Haystack).

4. Perhaps perform a measurement of relativistic echo delay at superior conjunction (upgraded Haystack required).

C. Mercury.

1. Mercury is the most favorable planet for carrying out the above mentioned relativity experiment (upgraded Haystack).

2. Redetermine orbit. Observe for several years to obtain another test of General Relativity by perihelion advance.

3. Better scattering property determinations.

4. Better rotation rate measurements.

5. Surface mapping.

D. Mars.

1. Measurements similar to those outlined for Venus should be made (ungraded Haystack can make many of them).

The availability of the large, precise Haystack antenna opens frequency regions at least as high as 8 Gc to radar astronomical investigations.* The present Haystack can achieve reliable detection (S/N > +6 db) after one day's integration on Venus and Mercury when close, but these planets cannot be followed completely around their orbits.

As stated earlier, an increase in overall performance of the Haystack system is required to perform many of the experiments. A blanket statement can be made that there is a direct trade-off between resolution and signal-to-noise ratio. It is thus perhaps worth repeating that, while a most important result of a 10-db increase in Haystack capability will be the ability to perform the fourth test of general relativity using Venus or Mercury at superior conjunction as targets, there are many other experiments that will be greatly improved in quality, such as the search for Venus atmospheric effects at X-band and the mapping of the surfaces of Venus and Mercury.

III. Ionospheric Studies

Since 1960 the Station has conducted research on the behavior of the ionosphere via the technique of incoherent backscatter observations at UHF and L-band. The 220-foot UHF (440 Mcps) system has both range and frequency resolution and is able to study electron concentrations and electron and ion

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*Another very important factor in such studies is determination of frequency dependence of the measured quantities. To date, only the West Ford site has made limited measurements of Venus and the moon at 8 Gc.

temperatures to altitudes between 100 and 700 km. Some 20 technical papers have been contributed by Station personnel based upon this work.

There has been interest on the part of the Army (Dr. Arendt, Ft. Monmouth) and NASA (J. E. Jackson, Goddard Space Flight Center) in correlating Millstone observations with those made from the topside sounder in Alouette. It is highly desirable that these studies continue since the Millstone capability is unmatched in these latitudes.

IV. Radiometric Work

Haystack will be operable later this year as a high-performance radio telescope at 10, 6 and 3.8 cm. Hopefully, a good capability at 2 cm and 0.8 mm can be made available also. Radiant flux and polarization measurements will be possible. Such measurements on planets may be helpful to NASA in designing probe missions for planetary studies.

The ability to correlate closely radar and radiometric measurements utilizing the same basic instruments is expected to lead to interesting results from combined radar-radiometric studies of lunar and planetary surfaces.

Later this year it is also expected that spectral line studies of various sources at OH- (Lincoln) and H- (Harvard) line wavelengths will be in progress.

System Implementation

I. Range Measurements Using the Presently Planned Haystack Components

As an example, let us discuss the radar upgrading required to permit the 4th Test of General Relativity using Mercury at superior conjunction as a target.

A. Signal-to-Noise Ratio in a CW Experiment

The parameters of the Haystack CW X-band radar as presently planned are listed in Table II. The antenna gain is the measured value and is probably not uncertain by more than $\pm$ 1 db. The transmitter power (100 kw) has yet to be realized, although the klystron has been tested at this power level by its manufacturer. The system temperature given (145°K) seems a likely value for what can be expected using the batch-cooled parametric amplifiers that will be used in an experiment in June 1965. The possibility that this temperature may be raised by the sun's brightness when observing planets nearly aligned with the sun, has been considered. At Millstone it was possible to observe Venus and Mercury when at an angular separation from the sun of 1.5°, with an increase in system temperature of 20°K. At Haystack the angular separation during the relativity experiment will be a minimum of 1°, but the radio temperature of the sun and the angular extent of the antenna beam are lower at X-band. Hence, we believe that the contribution of solar noise to the system temperature should be small ($\lesssim$ 10°K). This can be tested as soon as full steering capability of the antenna is realized.

The sum of the quantities in Table II yields a number (in decibels) which is the path loss allowed for an echo intensity equal to the noise level in a 1-cps filter. This is 345 db for the current Haystack X-band radar.

The actual bandwidths that would be employed for CW experiments against Mercury, Venus and Mars are given in Table I. For Mercury this value (20 cps) is that which would accept half the echo power assuming that Mercury scatters like the moon. The total (i.e., limb-to-limb) doppler spread is of the order of 200 cps, and a filter matched to this would introduce additional noise power that would not be balanced by a corresponding increase in echo power. The value of 200 cps for Mars has been arrived at similarly, while the value for Venus is based upon the X-band observations reported by K. Karp and W. B. Smith. Were Venus to scatter like the moon this receiver bandwidth should be set to about 20 cps. This difference demonstrates that at X-band Venus apparently is very different from the moon in its scattering behavior, despite the similarity at lower frequencies. It follows that the values for Mercury and Mars may be underestimates. Fortunately, the threshold after one second varies only as the square root of the bandwidth.

As shown in Table II, after 10,000 seconds* of integration, the threshold is improved 10 db, while allowing for the fact that only half the echo power is being received. Table I also gives typical values for the actual path loss for Mercury, Venus, and Mars based upon the best available cross-section measurements listed in Table III. It can be seen that only Mercury might be detectable at greatest distance, with the signal-to-noise ratio of only ± 0.5 db. A minimum useful value based upon experience at Millstone in attempting to observe Venus and Mercury would be +6 db.

From the actual path loss to Mercury in 1965 and 1966 plotted in Fig. 2, it can be seen that for the favorable superior conjunctions (June 1965 and May 1966) the path loss will be more nearly 354.2 db yielding a signal-to-noise ratio of +1.3 db. The uncertainty in this estimate is at least $\pm$ 4 db, but a more accurate estimate will be possible as soon as observations have been made at inferior conjunction in April 1965.

B. Initial CW Experiments Using Presently Planned Haystack

Because of the numerous uncertainties in our estimates of the nature of the radar detection problem for Mercury throughout its orbit, it is essential that certain preliminary experiments be carried out with the presently planned radar. Equipped with measured values in place of estimates, we can more reliably establish the required performance of the upgraded radar. These initial experiments are planned for the April inferior conjunction of Mercury.

*This is about the maximum practical integration time that can be employed in a day's operation where only about half the total time is available for receiving and integration.

TABLE III

Planetary Cross Section Measurements

	Mercury	Venus	Mars
Arecibo value (430 Mcps)	6%	14(?)%	4%
Russian value (700 Mcps)	6%	10%	?
Millstone value (1295 Mcps)	10%	13%	?
J. P. L. value (2400 Mcps)	5%	11%	3%
X-band value (7750 Mcps)	?	1%	?

The Varian VA-879 100-kw CW klystron will be driven by a high spectral purity source derived from an atomic standard. Phase or frequency modulation can be introduced in the exciter chain. Beam switching is provided to eliminate amplification of thermal noise from the klystron which might impair reception. Waveguide switches will be employed for duplexing. The R/C box is presently equipped with batch-cooled parametric amplifiers. Mixers and first IF amplifiers (130 Mc) are installed in the R/C box. All subsequent frequency translation and IF processing will be performed by equipment located in the control room. Successive IF frequencies of 30 and 2 Mcps are to be used with local oscillator frequencies of 100 and 28 Mcps. The planetary doppler shall be removed by offset in the 100-Mcps local oscillator with the possibility of supplementary offset at 28 Mcps. The generation of the shifted local oscillator signal shall be accomplished by using the Hewlett-Packard 5100-A frequency synthesizer. This device is capable of generating externally controlled local oscillator signals coherent with a standard frequency input of 5 Mc. Digitally controlled frequency increments of 0.01 cps are possible.

The terminal equipment currently available converts the 2-Mc IF signal to a 200-kc IF and thence to a 5-kc IF. The 5-kc/s signal may be recorded in analog form, while digital samples of the sine and cosine components of the 200-kc/s IF may be stored on digital magnetic tape. The present equipment is capable of handling signals having a bandwidth of 1 kc/s - adequate for the initial CW experiments on Mercury and Venus, but not for the range measurements that are to be described.

C. Range Measurements

It is proposed to determine the range to Mercury by phase coding the transmitted waveform and processing the echoes in the matched-filter delay line available at Millstone. This delay line will permit codes of up to

4 milliseconds in length to be employed with a baud length as short as 20 microseconds. The code length will be quite adequate to resolve any initial uncertainty in the range ($\sim \pm 1$ m. sec.) and the baud length is short enough to permit 10-microsecond range resolution to be achieved easily. The final choice of code will be made upon the basis of recommendations by R. Price.

The sine and cosine samples of the output from the matched-filter delay line will be sampled at 50 kc/s sample rate and recorded on digital magnetic tape. Later these tapes will be processed by a digital computer which will first synthesize a narrow-band (pre-detection) filter (20-cps wide) to make full use of the phase coherence in the echoes, and will then sum incoherently the rectified output of this filter.

For observations against a point target the signal-to-noise ratio would remain identical to that expected in the CW experiment outlined above. Unfortunately Mercury is not a point target, but one which is distributed in delay. Thus, the effective target cross section contributing to observations in which a short pulse is synthesized would be considerably less than the total value. Assuming that the synthesized pulse has a width of about 50 microseconds (in order to locate the leading edge of the planet to an accuracy of $\pm$ 10 microseconds) it is anticipated that this effect will introduce an additional 3-db loss in echo power. Thus the signal-to-noise ratio for the range experiment will become -1.7 ± 4 db at superior conjunction. In view of this, and the proven need of +6 db signal-to-noise ratio, we believe an increase in system sensitivity of at least 10 db to be necessary for an accurate experiment.

It should be stated that the loss incurred in resolving the target in range is common to all forms of modulation which would yield the required accuracy. R. Price has estimated, also, that the coded pulse scheme outlined above is probably slightly superior to most of the other practical schemes that might be tried. It has the additional advantage that with the exception of the high-speed data sampling and recording equipment required all the other major components are at hand.

It is possible to argue that the X-band measurements on Venus of D. Karp and W. B. Smith are in error and that this planet does scatter like the moon at this frequency. In this case the system threshold would be increased to 355 db and the path loss reduced about 347 db rendering the planet visible in a CW experiment with the present radar at superior conjunction. Unfortunately, because it is a larger body than Mercury, the effect of resolving the planet in delay is more serions. An estimated 9-db reduction in the cross section would be caused by synthesizing a 50-microsecond pulse, and hence, despite these favorable suppositions, we would expect the signal-to-noise ratio in the range experiment to be no better than that for Mercury.

To conclude this section, we may state that with the addition of only high-speed data sampling and recording equipment the CW radar can be converted to a range-measuring radar. The presently planned Haystack Radar will be inadequate to observe Mercury at superior conjunction even in a simple CW experiment, and the range experiment seems quite out of the question. A ten-fold increase in radar performance would remedy this situation.

The Required System Improvements

A. General

As has been pointed out in the previous section a means of achieving the required radar range accuracy can be implemented fairly readily. Estimates of the path loss to Mercury at superior conjunction, together with effective cross-section reduction resulting from range resolution and doppler spreading, show, however, that even with the Haystack antenna operating at X-band a ten-fold increase in system performance is needed to achieve a useful signal-to-noise ratio at the end of a day's integration (10,000 seconds).

In looking for a 10-db increase in system sensitivity, we have considered first reducing the system temperature. By employing a maser in place of the parametric amplifier and possibly by redesigning the waveguide and feed horn assembly it is thought that a 3-db improvement might here be made. The reduced system temperature ($75^{\circ}K$) probably represents the lowest value likely for observations of Mercury in close proximity to the sun. The breakdown of the contributions to this value is given in Table II.

It seems that the balance of the improvement must come from increasing the transmitter power. We note that the existing power supply would allow the operation of a 500-kw CW transmitter at 50% efficiency. An X-band tube of this capability is being developed at the present time.

A small increase in signal-to-noise ratio could be obtained by constructing a Rake radiometer. This has not yet been attempted for planetary observations, partly because of the complexity of the matched filter network and partly because the gain is likely to be small ($\sim < 2$ db).

Moreover, for a ranging experiment, the Rake radiometer would have to be iterated many times (say 100) to span the uncertainty in the range delay. We do not therefore plan to adopt this step.

It is evident from the preceding section that an average power of 500 kw is the minimum that might usefully be employed, and hence for a pulsed radar system the peak power might be required to be 50 Mw. No such transmitter seems likely to be available either now or in the near future. Accordingly, we must use a continuous waveform and code it in some fashion. The system that can most readily be implemented is the phase code technique discussed in the previous section. Secondly, high-speed data processing will inevitably be required to measure range to $\pm$ 10-microsecond accuracy. Thirdly, to build up the signal-to-noise ratio by addition of data taken over a period of a day or more will require extensive use of a digital computer.

B. System Design

It is not immediately obvious that if a new radar system is to be built it should be made to operate at X-band. A case could be made for lowering the operating frequency to 5000 Mc/s (C-band). In favor of such a decision are:

1. At C-band the effect of local weather on Haystack operation would be less serious.
2. Problems with high power in small microwave components would be reduced.
3. In future Venus observations any effect of its atmosphere in perturbing the scattering properties should be less.
4. In the present experiment the cross section of the leading range element should be larger than at X-band because the central "highlight" is brighter at lower frequencies, and also the doppler broadening is slightly less. These factors should offset to some degree the loss due to reduced ($\approx$ 4 db) antenna gain.

A decision to remain at X-band is favored by the fact that it seems unlikely that a 500-kw tube can be obtained for C-band operation in under two years. Delivery of X-band tubes in about 12 months is predicated on extending the performance of the Varian 879 or the Eimac 3030 klystron tube. The latter tube has produced under pulse conditions 2 Mw at 60% efficiency, and has been tested at greater than 200 kw for four-hour runs. It has also operated at an average power of 500 kw for shorter intervals.

Some improvement in the system temperature can be expected by using helium-cooled masers. In this area of development two choices are available. MEC is currently supplying 8-kmc traveling-wave masers to the National Bureau of Standards. A prototype of this device has been at the

Lincoln Laboratory for some time for evaluation. Basic components needed to support the operation of the traveling-wave maser are also available in-house at this time. We have a cavity-tuned maser and it is expected that one or the other of these devices could be deployed by the middle of 1965, and the system temperature might be reduced to $70^{\circ}K$. These two improvements would provide a ten-fold increase in system sensitivity, and yield a signal-to-noise ratio against Mercury at superior conjunction of $+8.3 \pm 4$ db. As stated previously, this estimate will be refined as soon as observations of Mercury are conducted in April 1965. The upgraded radar system, for planetary range observations, will be operated as shown in the block diagram of Fig. 15. In order to preserve our ability to operate Haystack with a minimum of interference by this program the existing Radar/Communications box will not be altered, and hence will always be available for use. For the high-power planetary radar work a new box will be fitted out with transmitter maser, receiver, and control equipment as an integrated assembly for use in the Haystack antenna.

C. Data Handling

There is ample reason to avoid, if at all possible, the generation of large numbers of raw-data tapes. However, no existing computer could process the data generated in an experiment of this kind* in real time. For this task, a super-speed special-purpose machine would be required. In lieu of a high-speed data processor we are (reluctantly) forced to solve the problem of data handling by digital storage on magnetic tape and subsequent non-real-time processing. In the worst case, when the planet is at superior conjunction and the range is not known a priori to better than ± 200 microseconds, some 6×10^8 data bits need to be stored per day. At Millstone a special-purpose machine

*Where range resolution approaching 1.5 kilometers (10 microseconds) is required.

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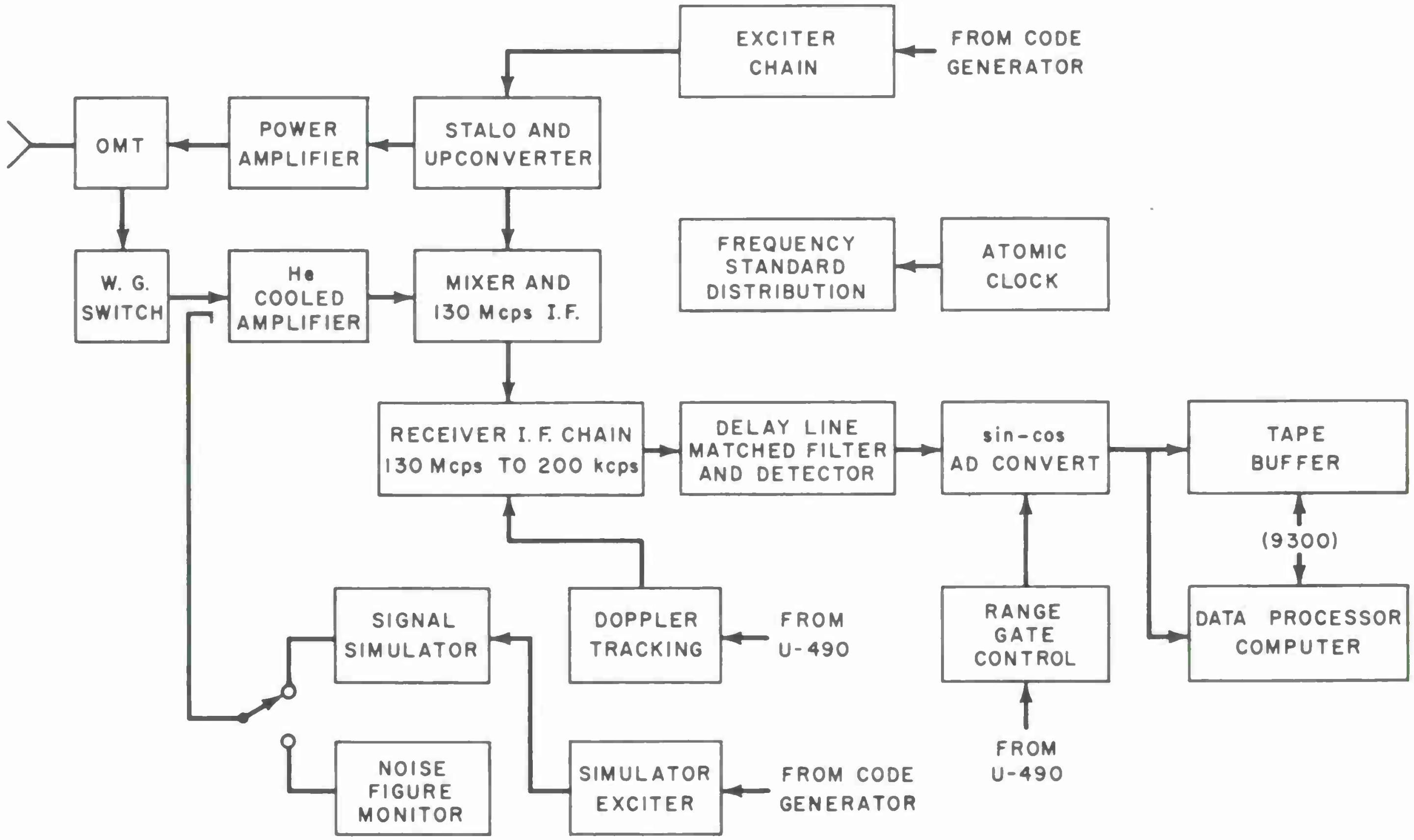

15. Haystack - High Power Planetary Radar.

is available to buffer digital data samples and store these on magnetic tape. This machine, however, would be unsuitable for a CW signal since it could not cope with the high-data rate. Either a new special-purpose device must be constructed, or a digital computer capable of acting as a buffer must be obtained. We favor the second alternative.

The existing Univac 490 Haystack computer is too slow for this application. (This would remain true even if it were not occupied with directing the antenna, controlling the doppler frequency of the receiver, and with tracking the echo in range.) Thus, we would propose to acquire a faster machine to act as a data handling device, i.e., to put the samples in proper format and record them on two or more tape units. At present an SDS-9300 seems the most suitable choice. Although the cost of this approach may be higher than that of a special-purpose machine, the savings in engineering time will be considerable. Supporting arguments are:

1. When not in use for data recording the computer is available for analysis of the data which this (and several other experiments) will generate in large quantities.
2. If an auxiliary high-speed preprocessing unit can be provided later, it can be used with the 9300 to provide a real-time coherent analysis capability.
3. A special-purpose data recording unit would throw the processing load onto the 7094 computer at the Laboratory, as the processing time (of the order of ten times real time) would be so long that our present computers could not keep pace.

Conclusion

The program outlined above can be carried out generally within the manpower allocated to our Radio Physics Program. Instrumentation costs, and time schedules have been prepared for separate submission. As a result of the improved radar transmitter for Haystack, the Millstone Hill Field Station facilities will achieve clear preeminence in the broad field of precision radar measurements of natural and manmade objects in deep space. Important refinements of our fundamental unit of length in the solar system, the astronomical unit, can be made. More precise determinations of the orbits of the near planets will be possible, and deductions of other characteristics will be a result of these measurements. A 4th test of general relativity will be possible along with a more accurate corroboration of the precession of the perihelion of Mercury. The precision determination of the orbits of artificial satellites, even when silent, will be possible with facilities at the Millstone Hill Field Station.

25 January 1965

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13. ABSTRACT

An approach to the construction of a radar employing the 120-foot Haystack antenna at a wavelength of approximately 4 cm, a transmitter capable of producing 500 kw of average power, and a maser preamplifier for the receiver is described. The system is expected to have a threshold (signal to noise in a 1-cps filter) of 355 decibels. Extended integration can increase this factor by about 10 decibels. This radar performance will permit measurements on the inner planets of the solar system throughout their orbital period. Measurements on Jupiter can also be attempted, and a possible detection of Saturn is implied. Experiments exploiting this performance are described, including the conduct of a fourth test of general relativity, the precision determination of the orbits of the inner planets, a measurement of the astronomical unit with increased accuracy, better determination of planetary masses and radii, and measurements on planetary surfaces. These measurements are not only of interest to astronomers and cosmologists but also of critical importance to the accurate guidance and navigation of vehicles in space. The roles played by the (L-band) Millstone radar tracker, and (UHF) ionospheric radar in current space research are also briefly discussed.

14. KEY WORDS

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